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STUDY OF CROSSED-FIELD AMPLIFIERS

Report Nr. 9
Contract Nr. DA 36-039 AMC-02164(E)

Ninth Quarterly Progress Report
16 June - 15 September 1965

United States Army Electronics Command
Fort Monmouth, New Jersey

ELECTRONICS RESEARCH LABORATORY

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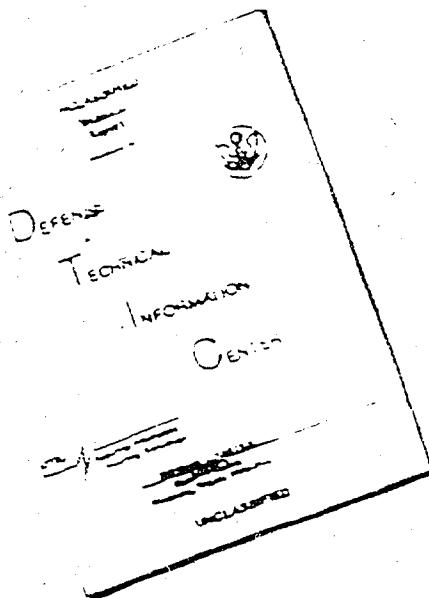
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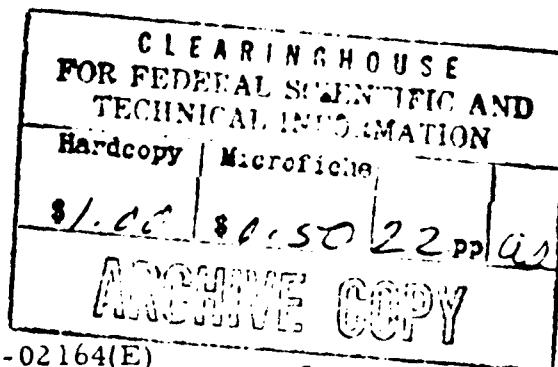
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University of California
Berkeley, California

Quarterly Progress Report   Study of Crossed-Field Amplifiers
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This report presents progress on research in crossed-field
amplifiers for the quarter ending 15 September 1965. In the past,
major stress has been placed upon the important problem of noise iden-
tification and reduction. It has been shown that the gun design and the
proper injection of the beam into the interaction region, are key ele-
ments in low noise performance. As a consequence of this and other
work, major improvements in the noise performance of crossed-field
tubes have been made during the preceding year. Work is continuing
on the synthesis of guns for even better injection, on the study of the
interaction region, and on the cathode region. Important experimental
results were also obtained during this period verifying a novel statis-
tical theory of the smooth-bore magnetron. This substantially com-
pletes this task. Work will continue on all other phases during the
following quarter, and studies will begin on related crossed-field inter-
actions in solids.

The work is directed by Professors T. Van Duzer and J. R.
Whinnery, and Dr. S. P. Yu. Dr. Yu of Litton Industries, San Carlos,
California, has been appointed on a part-time visiting basis for the
current academic year.

SHIELDED-GUN LOW NOISE AMPLIFIER
(R. A. Rao, Professor T. Van Duzer, and Dr. S. P. Yu)

The objective of this project is to design and test a crossed-
field electron gun in which the cathode region is shielded from the

magnetic field. As part of the project, a method for synthesizing crossed-field electron guns was developed. It has been used to synthesize an electron gun in which the electron beam has Kino flow characteristics near the cathode and Brillouin flow characteristics near the drift region.

In the present report period the electron gun was fabricated and tested. The operating characteristics of the tube were found to be in very good agreement with the theory. A major objective of the experiment was to take pictures of the beam so that the beam shape in the experimental tube may be compared with the theoretical beam shape. The tube has a palladium leak through which small amounts of hydrogen gas may be introduced into the tube. A titanium pump/gauge was used to control the pressure in the tube. For the operating conditions of the tube, a pressure of 2×10^{-6} mm of Hg was found to be optimum for photographing the beam. At pressures of this order, it can be shown that the space charge conditions in the tube are affected very little by the ionization of the gas. At the same time, the beam appears intense enough to be photographed. The beam was viewed through a strip of first surface mirror mounted outside the tube. The tube was aligned in the magnetic field by rotating the tube until the beam transmission to the collector was maximum. At this position the cross-section of the beam hitting the collector was centered in the collector and appeared very straight. The pictures were taken on Kodak Tri-X film with a 35mm Edixa reflex camera with a standard 50mm lens. In the first pictures the intense light from the cathode and the heater completely washed out the beam near the cathode. To overcome this difficulty, a narrow band "Spectra-coat" filter (Optics Technology, Inc.) was used. Hydrogen has a strong atomic line at 4861 Å which lies in the blue part of the visible spectrum. The light from the hot cathode has most of its energy in the red part of the visible spectrum and hence the interference from the cathode light may be greatly reduced by using a narrow band filter with its center frequency near the 4861 Å line of hydrogen. A filter with a pass band of about 250 Å centered around 5000 Å was used. With this filter an exposure of 15 min. at f/5.6 was necessary for negatives of good density on Kodak Tri-X film. It was necessary

to enclose the tube and the camera in a light-tight black box to avoid reflections from the tube and the mirror. Figure 1 shows the electron gun and the electron beam. The electrodes were exposed for 1/125th sec. at f/5.6 with artificial light. In spite of the filter, light from the heater and reflection in the anoide are evident in the picture. In Figure 2, the electron gun and beam from the photograph are compared with the theoretical electron gun and beam.

The right-hand beam-forming electrode appears to be a little higher in the tube than in the design. This may be partly due to the error in assembly and partly because it is difficult to determine the profile of the gun electrodes accurately from the photograph. Apart from this, the beam shape seems to be in good agreement with the theory. The beam thickness in the drift region also agrees very well with the theoretical Brillouin thickness used in the design.

In the next report period, the design of the shielded-gun tube will be continued.
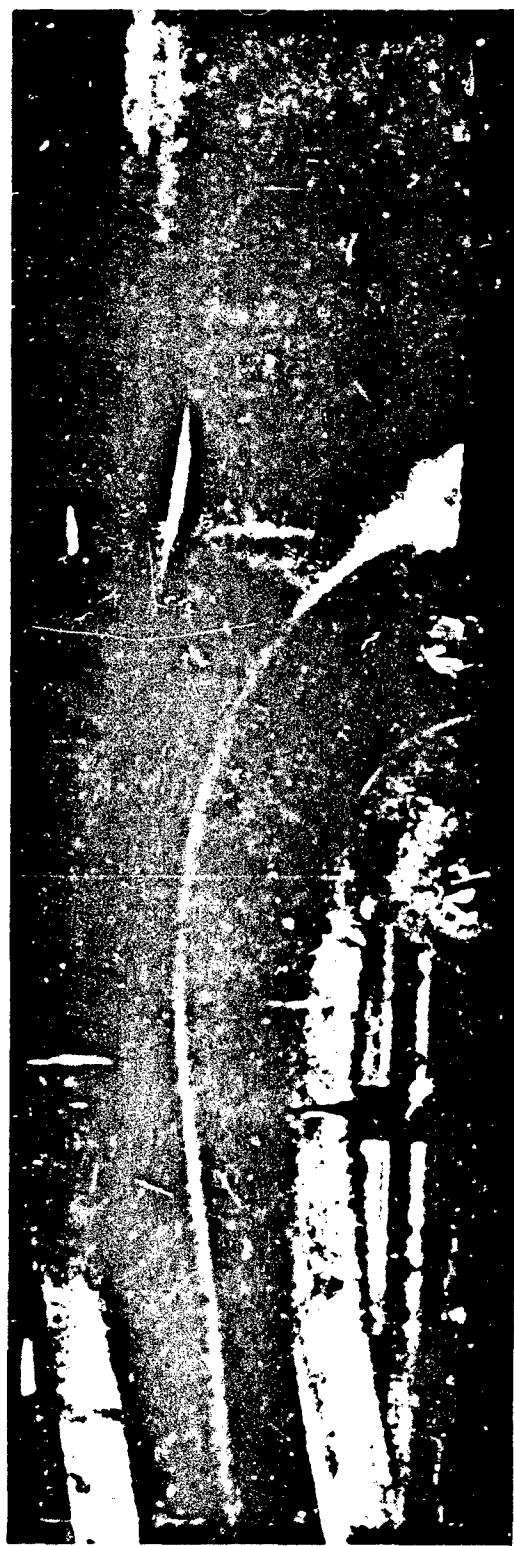
Fig. 1. Photograph of electron gun and beam.
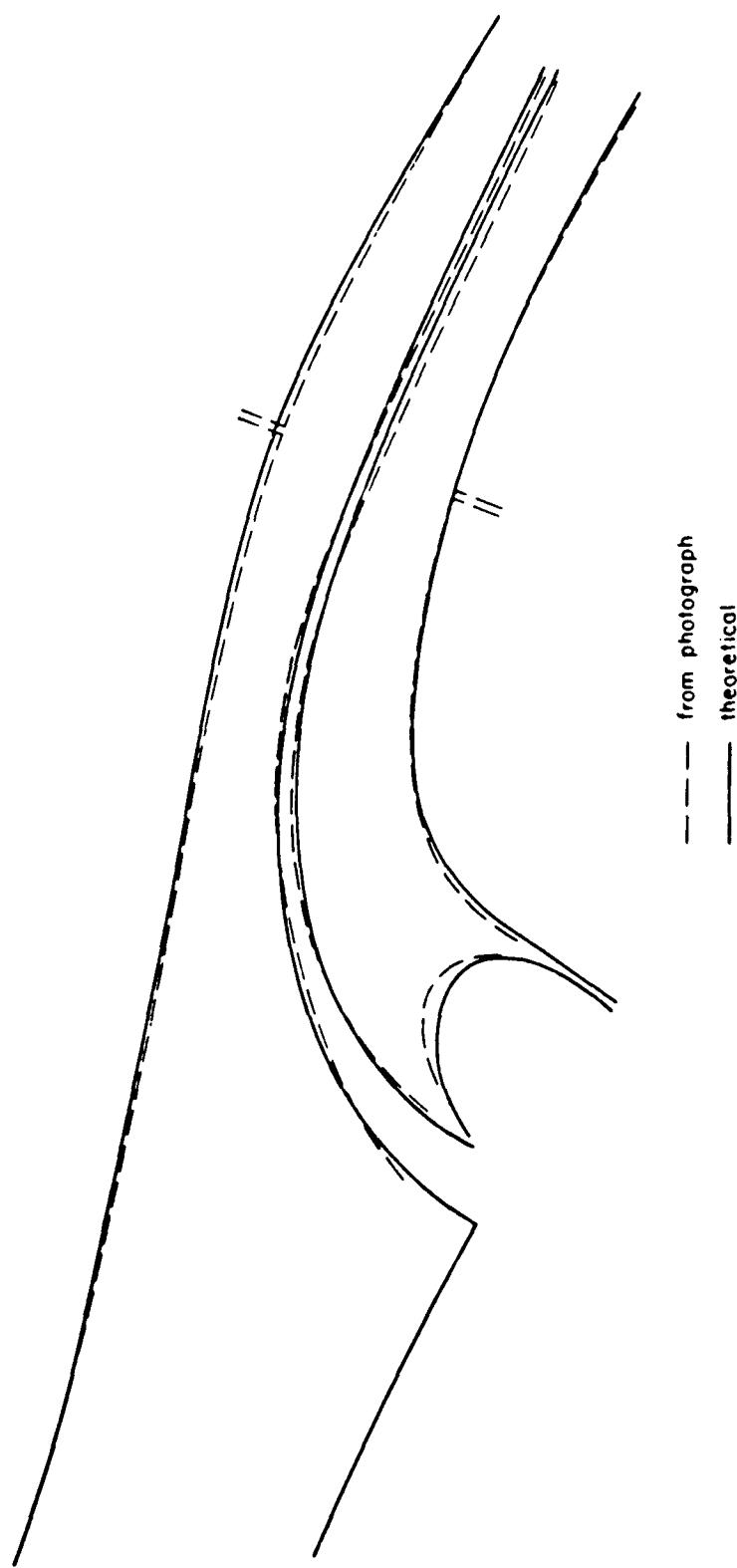
Fig. 2.   Comparison of experimental and theoretical beam shapes.

— — — from photograph

———— theoretical

SYNTHESIS OF BEAMS FOR CROSSED-FIELD AMPLIFIERS
(Gene A. Poe, Professor T. Van Duzer, and Dr. S. P. Yu)

The objective of this project is to evaluate second-order correc-
tions to the solution of the first-order paraxial-ray equation. The par-
ticular beam flow under consideration is a sheet beam in crossed
electric and magnetic fields subject to boundary conditions of the Kino
flow near the cathode and the Brillouin flow at the exit plane.

A solution to this problem has been obtained by Rao[1] using the
first-order paraxial-ray equation. The effects of second-order correc-
tions to this particular solution will be studied here.

The paraxial-ray equations are formulated using an orthogonal
curvilinear coordinate system such that one coordinate corresponds to
a typical electron trajectory. (See Figure 3.) Distance measured along
q_2 is defined by Eq. 1, where $\overset{\circ}{\varsigma}$ is the scale factor for the q_2
direction.
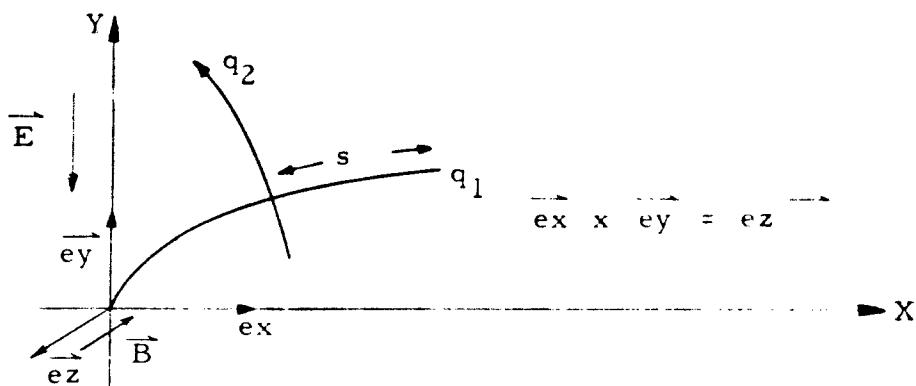
Fig. 3. The curvilinear coordinates for
the paraxial-ray equations.

$$\text{Distance along } q_2 = \int_0^{Q_2} \varsigma\, (S,\ q_2)\, d\,q_2 \tag{1}$$

For convenience the scale factor along the q_1 axis is chosen to be
unity and the distance along the q_1 axis is denoted by S.

[1] R. Rao. "Study of Crossed-Field Amplifiers." Fourth Quarterly
Report. April to July '64. Electrons Research Laboratory. Univer-
sity of California, Berkeley, California.

It can be shown that this particular coordinate system lends itself to working only with scalar quantities and the three paraxial-ray variables are potential, ϕ; curvature for the q_1 coordinate, k; and the scale factor for the q_2 direction, $\dot{\xi}$. Using a Taylor series expansion for $\dot{\xi}$ about $q_2 = 0$, the central trajectory, one obtains:

$$\dot{\xi}(S, q_2) = \overset{\circ}{\dot{\xi}}(S, O) + \left.\frac{\partial \dot{\xi}(S, q_2)}{\partial q_2}\right|_{q_2=0} q_2 + \cdots \qquad (2)$$

The paraxial formulations are found by taking only a few of the terms in this series expansion. Keeping only the first term in Eq. 2, one obtains the first-order paraxial-ray equation; and letting,

$$\dot{\xi}(S, q_2) = \dot{\xi}(S, O) + \left.\frac{\partial \dot{\xi}(S, q_2)}{\partial q_2}\right|_{q_2=0} q_2 \qquad (3)$$

one obtains a second-order paraxial-ray equation. For convenience, one denotes $\dot{\xi}(S, O)$ by $\dot{\xi}$, and $\left.\frac{\partial \dot{\xi}}{\partial q_2}\right|_{q_2=0}$ by $\dot{\xi}_q$. Higher-order paraxial-ray equations can be found by adding more terms to Eq. 3.

The first-order paraxial-ray equation expressed in normalized units can be written as follows:

$$2\phi\, \dot{\xi}''_1 + \phi'\, \dot{\xi}'_1 + \left(\phi'' + 4k^2\phi + 1 + 2k\sqrt{2\phi}\right) \dot{\xi} - \frac{1}{\sqrt{2\phi}} = 0 \qquad (4)$$

The second-order paraxial-ray equation can also be expressed in the same normalized units and is as follows:

$$\left(4\phi k\, \dot{\xi}_1 + 8\phi k'\, \dot{\xi}_1 - \frac{2\phi'\, \dot{\xi}_1}{\sqrt{2\phi}} + \sqrt{2\phi}\, \dot{\xi}_1^{\,\prime} \right) \dot{\xi}_1^{\,\prime}$$

$$+ \left(-5\phi'' k \dot{\xi}_1 - 20\phi k^3 \dot{\xi}_1 - 17k \dot{\xi}_1 - 20k^2 \sqrt{2\phi}\, \dot{\xi}_1 - \frac{4\phi'' \dot{\xi}_1}{\sqrt{2\phi}} - \frac{5\dot{\xi}_1}{\sqrt{2\phi}} \right.$$

$$\left. + 5\phi' k' \dot{\xi}_1 + 2\phi k'' \dot{\xi}_1 - \frac{\sqrt{2\phi}}{4} \left(\frac{\phi'}{\phi} \right)^2 \dot{\xi}_1 \right) \dot{\xi}_1 + \phi' \dot{\xi}_q^{\,\prime}$$

$$+ \left(\phi'' + 4\phi k^2 + 1 + 2k\sqrt{2\phi} \right) \dot{\xi}_q + 2\phi\, \dot{\xi}_q^{\,\prime\prime} + \frac{10k\, \dot{\xi}_1}{\sqrt{2\phi}} + \frac{3\dot{\xi}_1}{\phi} = 0 \qquad (5)$$

In Eqs. 4 and 5 the magnetic field is directed along the negative z-direction and the prime superscripts denote differentiation with respect to the arc length, S, along q_1.

Using the solution given by Rao to the first-order paraxial-ray equation, one solves Eq. 5 for $\dot{\xi}_q$, the second-order scale factor; however, unlike the first-order ray equation, one must have values for the first and second derivatives of the curvature, k, before the second-order equation can be solved for $\dot{\xi}_q$. Several methods of interpolating and differentiating the curvature were studied and Newton's, Stirling's and Bessel's formulas were found to give very reliable results.

The second-order paraxial equation was solved on a computer (IBM 7094) using Gill's[2] variation of the Runge-Kutta method. The results obtained thus far are in the process of being checked by employing smaller interval sizes of integration in the computer program. The curve in Fig. 4 shows the second-order scale factor plotted as a function of the arc length along q_1.

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[2] S. Gill. "A Process of Step-By-Step Integration of Differential Equations in an Automatic Digital Computing Machine." Proc. Camb. Phil. Soc., 47. 1951, pp. 96-108.
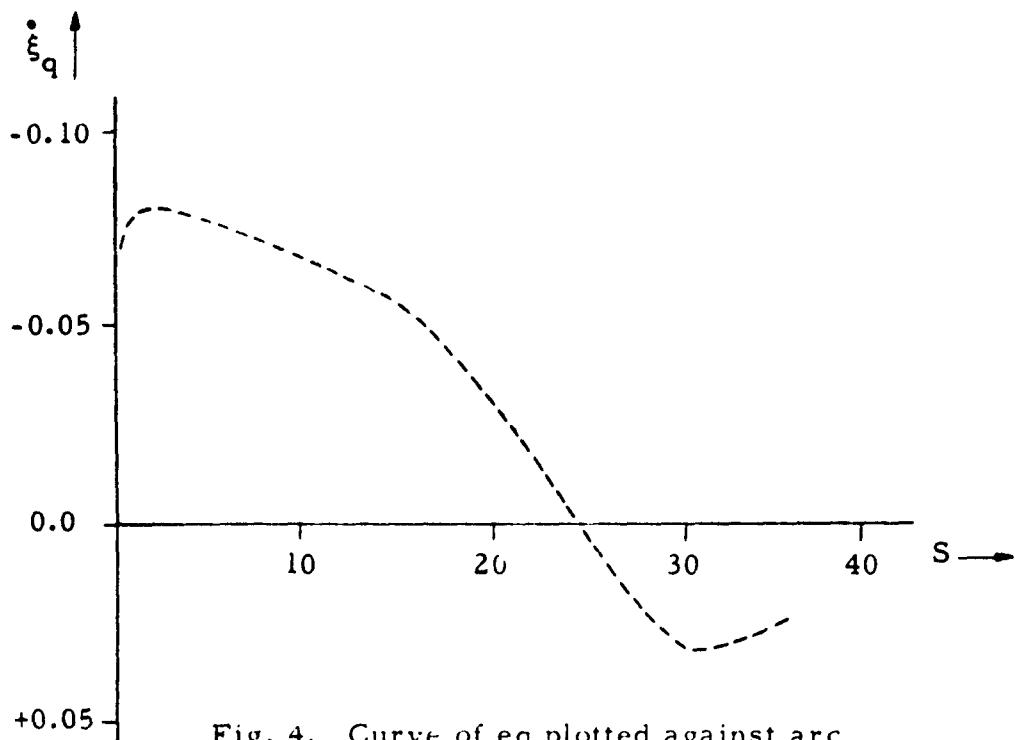
Fig. 4. Curve of $\dot{\xi}_q$ plotted against arc
length along central trajectory.

The first and second-order half beam widths are defined as follows:

$$\text{First-order half beam width} = \dot{\xi}_1 L, \tag{6}$$

$$\text{Second-order half beam width} = \dot{\xi}_1 L + \frac{1}{2} \dot{\xi}_q L^2, \tag{7}$$

where L is half the width of the cathode. Since the level lines of the q_1 = constant are approximated by straight lines in the first-order theory and by circular arcs in the second-order theory, Eqs. 6 and 7 cannot be compared until they have been plotted on the q_1 and q_2 coordinate plane. This is being done and, at this point, it appears that the second-order corrections to the first-order half beam width are very small.

FORWARD-WAVE NOISE-FIGURE STUDIES

(A. Sasaki, Professor T. Van Duzer, and Dr. S. P. Yu)

The aim of this work is to develop sufficient understanding of
the noise characteristics of forward-wave crossed-field amplifiers to
permit appreciable noise-figure reductions. The normal mode approach
will be used in the study of noise-transducing schemes.

By using normal mode amplitudes and coupled-mode equations
we seek to derive an expression for the minimum noise figure of a
crossed-field amplifier. The kinetic power carried by the beam waves
in an O-type amplifier is described by

$$\underline{P} = \frac{1}{2} \mathrm{Re} \left(U_z I_z^* \right) = \frac{1}{4} w^\dagger R w, \tag{1}$$

where $\dagger$ denotes the Hermitian conjugate, Re indicates the real part
of $U_z I_z^*$ (the product of the kinetic potential and the ac current in the
beam direction),

$$w^\dagger = \begin{bmatrix} U_z^* & I_z^* \end{bmatrix}, \tag{2}$$

and

$$R = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}. \tag{3}$$

However, in the case of a crossed-field amplifier, the kinetic power is
given by

$$P = \frac{1}{2} \mathrm{Re} \left(U_L I_L^* + U_T I_T^* + \phi I_L^* \right), \tag{4}$$

where ϕ is the ac potential defined by the product of the ac displacement
and the dc electric field. Here, we use the coordinate system in which
one coordinate direction is along the beam path (indicated by the

subscript L), the other is the direction transverse to the beam path (indicated by the subscript T), and the third is the direction perpendicular to the plane defined by T and L directions. This particular choice of coordinates avoids the complexity of analysis for the accelerating region where the electron beam is bending and makes the study of minimum noise figure possible. We introduce the R and w matrices of the crossed-field amplifier to express the kinetic power in the matrix form:

$$
R = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & \dfrac{1}{k_b} \\ 1 & 0 & -\dfrac{1}{k_b} & 0 \end{bmatrix} , \tag{5}
$$

and

$$
w^\dagger = \begin{bmatrix} U_T^* & U_L^* & I_L^* & I_T^* \end{bmatrix} , \tag{6}
$$

where k_b is the beam conductance of the electron beam in crossed fields. The matrix form of the kinetic power is used for the minimum noise-figure studies.

For the analysis of minimum noise figure, we assume that the region beyond the potential minimum in a crossed-field amplifier can be represented by a linear, lossless transformation. Linearity follows from the small signal assumption. However, the question might arise whether the dioctron effect, by which ac currents grow in a drifting region, prevents the drifting region from being represented by a lossless transducer. This question is resolved by writing the kinetic power expression in terms of the normal mode amplitudes. The transformation of noise fluctuations along the beam (magnitude of the Fourier component of the noise fluctuations at angular frequency ω) is given by

$$w_b = M w_a \tag{7}$$

because the noise quantities at the position b are represented by a linear combination of the noise quantities at the position a. Since the region beyond the potential minimum is lossless, the kinetic power must be conserved, which requires

$$w_b^\dagger R w_b = w_a^\dagger R w_a . \tag{8}$$

The use of Eqs. 7 in 8 gives us

$$M^\dagger = R M^{-1} R^{-1} , \tag{9}$$

which holds for any crossed-field amplifier. This matrix equation will be used to find the invariant noise parameters in order to determine the minimum noise-figure. In the coming period, the minimum noise-figure studies will be continued.

BACKWARD-WAVE NOISE-FIGURE STUDIES
(N. R. Mantena, Professor T. Van Duzer, and Dr. S. P. Yu)

Noise figure calculations on the backward-wave amplifier have been completed and are in excellent qualitative agreement with experimental results. Quantitatively, the difference between theoretical and experimental noise figures is found to be 6-7 db. This difference was also found for the forward-wave amplifier. In these, as well as the forward-wave calculations, it is found that the position fluctuations dominate over the other fluctuations. Space-charge reduction of noise figure in backward-wave amplifiers is also explained by this theory. Also, the noise-figure variation with beam current is in good qualitative agreement with experiment.

We sought to explain the quantitative difference of 6-7 db between the theoretical and experimental noise figure by assuming a finite initial correlation between the noise quantities at a plane slightly above the

potential minimum. However, even for hundred percent initial correlation, the theoretical noise figure is changed only for a small fraction of a decibel. Hence, the use of the experimental values of the noise-figure in the noise-matrix inversion scheme results in unphysical values for the noise quantities at the cathode.

Experiments with the modified long gun have been completed. It is found that the noise-figure increases with increased space-charge loading for this gun configuration. The variation of noise-figure with beam position is similar to that obtained for the Kino short gun and the Charles gun. The measured noise-figure is several db larger than for the Kino short gun.

A final report on this project will be completed during the next quarter.

CATHODE-REGION STUDIES
(R. Y. C. Ho, Professor T. Van Duzer, and Dr. S. P. Yu)

The aim of this work is to study the effect of the crossed magnetic field on potential minimum stability. The method used in this study is to form a relatively simple, space-charge feedback model for calculating the shot noise factor, $\Gamma^2 = \left(1 + \dfrac{i_f}{i_s}\right)^2$, where i_s is the emission perturbation current, and i_f is the feedback perturbation current so as to explain the noise phenomena in crossed-field devices.

It is suspected that the potential minimum instability may be closely connected with the termination of β-electrons on the cathode. The β-electrons are defined as those electrons which pass through the first critical planes. Since there are many classes of electrons in β-electron group, that is, for each pair of emission velocities there is one critical plane, the half-Maxwellian initial velocity distribution in the normal direction and full-Maxwellian initial velocity distribution in the transverse direction are taken into account in the β-electron termination feedback model. The β-electron feedback is being modeled as follows: (1) a d-c potential distribution which is uniform in the

transverse direction is assumed; (2) all the feedback currents are originated at the potential minimum, since the average position of the first critical planes are always close to the potential minimum. A computer program has been writen for this model, however, no calculations have been made because the potential minimum parameters, V_m and Y_m, have not been specified, which, we believe, are important in forming the complete feedback model.

At present, a relatively simple approximate method is being sought for determining the relation of V_m and Y_m. The problem was first treated by determining the space charge density and solving the Poisson's equation. The resulting analysis turned out to be complex. A simpler model results if the beam current density is assumed to be constant. However, this approach leads to a single equation relating the ratio of beam current density to the emission current density, V_m, Y_m, and the magnetic field. Without a second equation the potential minimum parameters V_m and Y_m cannot be determined separately. Further attempts will be made to evaluate V_m and Y_m.

In the next period we will do the computer calculation of feedback model so as to determine the shot noise factor as a function of crossed magnetic field.

CHARACTERISTICS OF THE SMOOTH-BORE MAGNETRON
(K. Mouthaan and Professor C. Susskind)

This project was essentially completed during this quarter. A final report entitled "Statistical theory of electron transport in crossed fields" by K. Mouthaan has been submitted to AEL for approval.

Also completed during the past summer were the experiments mentioned in the last report. These were conducted at Litton Industries in San Carlos, California. The experimental configuration is shown in Fig. 5. Experimental values of anode current were obtained for a range of anode voltages at several values of magnetic field, for two values of pressure. The experimental points follow the predicted dependence on
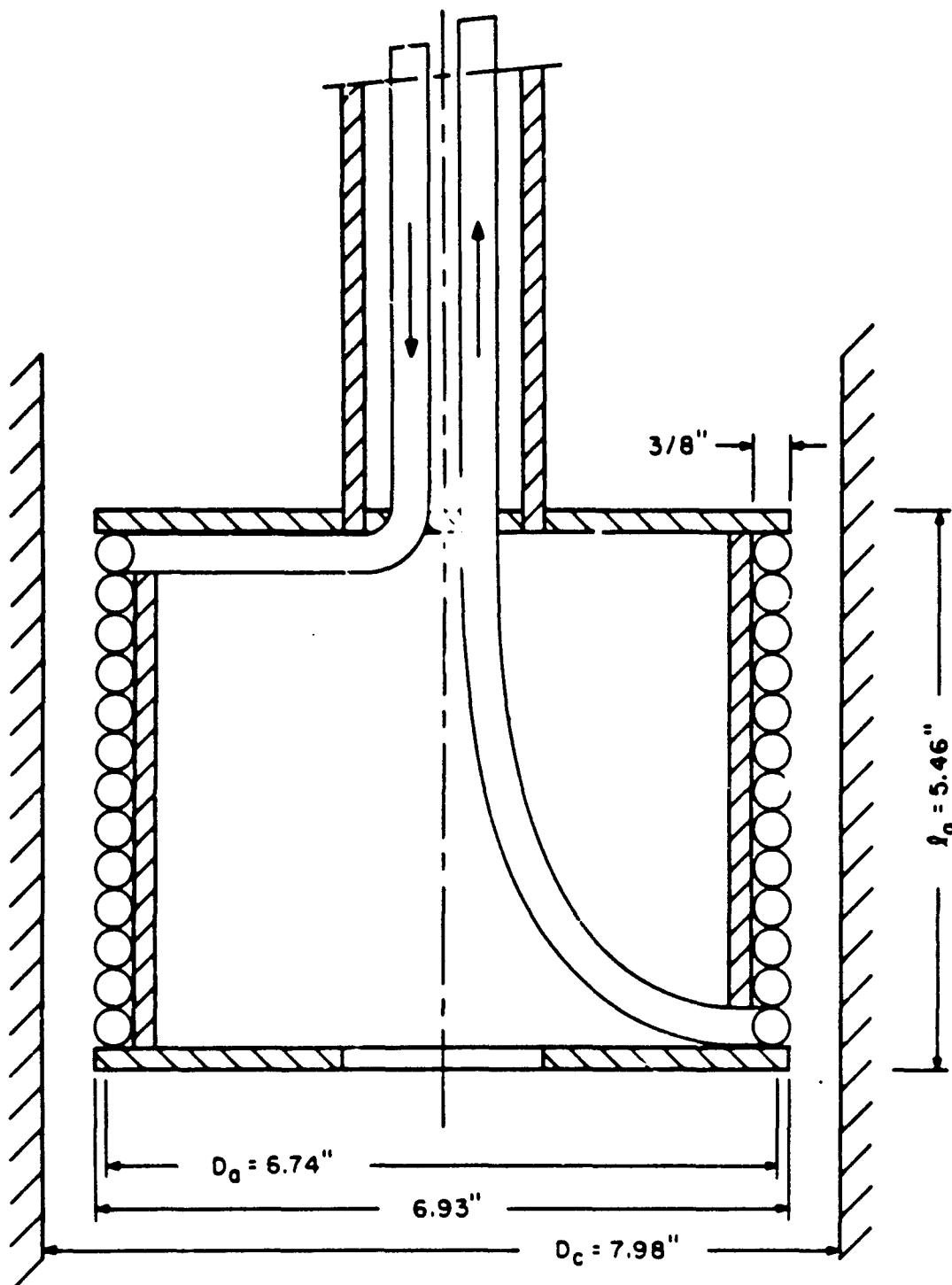
Fig. 5. Configuration and dimensions of smooth-bore
magnetron. Average anode diameter D_a is
equal to 6.93 - 3/16 in. Cathode-anode spacing
$d = (D_c - D_a)/2 = 0.62$ in.

$(V_a/B)^3$ extremely well; actual values obtained differ by a factor of 1/3.75 from those predicted on the basis of an ideal configuration, a discrepancy ti at is doubtless accounted for by such factors as non-uniformity of the beam in the axial directions, effective cathode emitting area being smaller than total area, and misalignment (since current density is inversely proportional to the fifth power of the cathode-anode spacing).

The finding that the experimental anode current is indeed proportional to $(V_a/B)^3$ provides an important confirmation of the theory. The proportionality is a direct consequence of the description of electron transport in the smooth-bore magnetron as diffusion, with the diffusion coefficient proportional to the square of the impressed electric field and inversely proportional to the cube of the magnetic field.

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ng a novel statistical theory of the smooth-bore magnetron, are also
d.

KEY WORDS	LINK A		LINK B		LINK C	
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